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INFRARED THERMOGRAPHY APPLICATIONS FOR BUILDING INVESTIGATION

BY

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Abstract. Infrared thermography is a modern non-destructive measuring method for the examination of redeveloped and non-renovated buildings. Infrared cameras provide a means for temperature measurement in building constructions from the inside as well as from the outside. Thus heat bridges can be detected. It has been shown that infrared thermography is applicable for insulation inspection, identifying air leakage and heat losses sources, finding the exact position of heating tubes or for discovering the reasons why mold, moisture is growing in a particular area, and it is also used in conservation field to detect hidden characteristics, degradations of building structures. The paper gives a brief description of the theoretical background of infrared thermography.

Key words: infrared thermography; examination of buildings; emissivity; nondestructive method.

1. Introduction

Infrared radiation (IR) was discovered by William Herschel in 1800 and after the discovery of the thermoelectric effect by Thomas Johann Seebeck in 1821, scientists have constantly been preoccupied to measure this long wave radiation with the help of thermocouples and thermophiles.

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The techniques used to find a diagnostic and a test method for the buildings structures are divided into destructive, semi destructive and non-destructive methods. Non-destructive testing methods are non-invasive techniques used to determine the integrity of a material or a structure and to quantitatively measure some characteristic of an object. Unlike destructive testing methods, non-destructive techniques can make an assessment without doing harm, stress or irrecoverable damage to tested objects.

Infrared thermography is a non-destructive investigation technology. It has been used for the last 30 years to test and diagnose buildings, structures and most likely cultural heritages. It proved itself to be an effective, convenient and economical method used in the conservation field to detect hidden characteristics of building structures (pre-existing forms, structural changes, structural abnormalities, presence of cavities), to show the morphology, to evaluate HVAC (stands for Heating, Ventilation, and Air-Conditioning) system performance, to detect degradation (cracks), to identify air leakage sources, to determinate heat losses, to map moisture, insulation and to evaluate conservation treatments (strengthening operations), (Ostrowski *et. al.*, 2003; Gamidi, 2009; Bianco & Ceradini, 2010; Nuzzo *et. Al.*, 2010).

2. IR Thermography Fundamental Operating Principles

Fundamentally, the thermography is based on the emission of objects but the functional principle of IR thermography coincides with three essential radiation laws:

1. *Kirchhoff's law of thermal radiation*, establishes the relation between emission and absorption of energy, indicating that a body which absorbs much also emits much and, according to this principle, the emission coefficient, ε, is introduced in equation as the ratio of emissivity, E, of a real body to the emissivity, E_z , of the black body under the same temperature $\varepsilon = E / E_s$. The emission coefficient, ε, is non-dimensional and takes values between 0 and 1 and depends on the wavelength, on the temperature and the surface texture of the body.

2. *Planck's law of radiation* describes the specific spectral radiation I' emanating from the idealized black body

$$I'(\lambda,T)=\frac{2\pi hc^2}{\lambda^5}\cdot\frac{1}{\mathrm{e}^{hc/\lambda kT}-1}, \qquad (1)$$

where: λ is the wavelength, T – the absolute temperature, h – the Planck constant and c – the speed of light. If the specific spectral radiation, I, is plotted over the wavelength, λ, as a function of temperature, typical Planck curves will result. In them it can be seen that the maximum of the curves shifts with growing temperature towards a smaller wavelength according to the Wien displacement law, $\lambda = b/T$, where λ is the peak wavelength, T is the absolute temperature of the black body, and b is a constant of proportionality called Wien's displacement constant equal to $2.8977685(51) \times 10^{-3}$ m·K (Mohr, 2008).

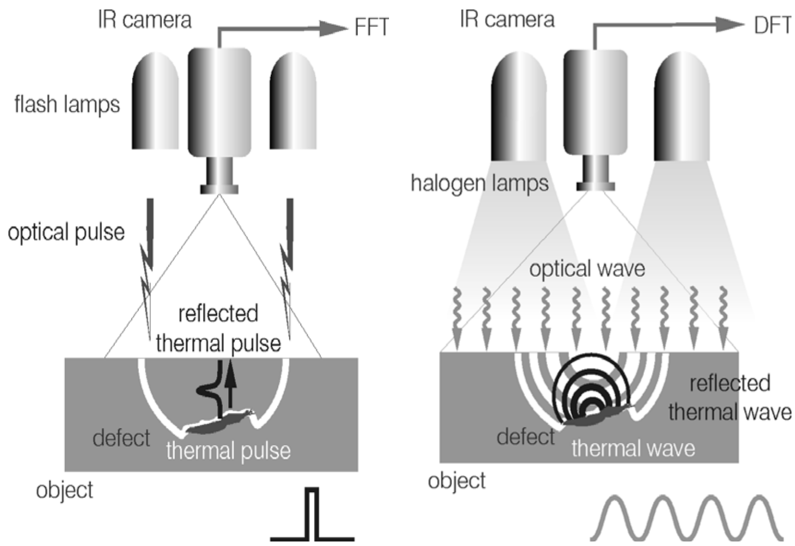
3. *Stefan–Boltzmann law*, applied to the emission of a surface over all wavelengths, integrated the Planck law and discovered that the radiant power, I, [W/m^2], grows with the fourth power of the temperature, $I = \sigma T^4$, where $\sigma = 5.67 \times 10^{-8}$ W/m^{2}K^4.

3. Applications of IR Thermography in Non-Destructive Evaluation of Structural Systems

The thermographic scanning system can measure and view temperature distribution based on IR radiations emitted from a heated surface of an object without physical contact between the measuring equipment and surface investigated, at the time of the test. As a result, a thermal two-dimensional image of the object is obtained, in different shades of colours or a gray scale. The principle of measuring test is based on the fact that any material continuously emits energy (electromagnetic radiation) proportional to their surface temperature. This energy depends on the spectral properties (emissivity, reflection), thermal properties (conductivity, the capacity of the material itself to transmit heat, specific heat, thermal diffusivity) and other physical properties of the material (porosity, density, water content*),* (Binda *et al*., 2011; Scrivener, 1992).

In order to obtain measurable temperature differences on the surface of an observed element, a previous heating of the surface is necessary. This can be obtained by a passive or an active method. The static (passive) thermography technique is achieved by using solar radiation, in order to record the thermal images without applying an external system of heating or cooling and under normal environmental conditions. The temperatures measured are influenced by three factors: *surface configuration, surface conditions* and *environmental system*. The surface configuration determines different insulating abilities and various values of thermal conductivity (air voids and low density areas determine lower thermal conductivity). The surface condition has a deep effect on the surface emissivity (higher values for rough surface and lower values for smooth surface). The environmental system (solar radiation, cloud cover, ambient temperature, wind speed, surface moisture) that surrounds the surface affects the validity of the image interpretation. After establishing the proper conditions for examination, recording images could be performed during the natural cooling process in the night time, when the solar radiations are no longer present. Most anomalies will be detected in the thermographic image areas showing cooler temperatures than the adjacent areas. A daylight analyse will show reversed results - the damaged areas will show higher values of temperature. This technique is frequently used when testing large areas, providing a low cost heat source and leads to an even distribution on the tested surface (Stimolo, 2003; Guidebook, 2002).

The dynamic (active) termography is frequently chosen to examine the inside of a building, using an external source of irradiation (IR). The energy is delivered into the object in the dynamic periodic way (lockin thermography) or in the dinamic single-shot way (pulse thermography). Heat penetrates the investigated object and the surface temperature distribution depends on the thermal properties of the material and its internal layers. Inhomogeneities, defects in the surface of the investigated object will be detected in measurable differences of temperature (disturbing the heat flux) in the local area of the surface, during the cooling-down process (Wiecek & Poksinska, 2007; Maierhofer & Roelling, 2009).



a *b*

Fig. 1 – Pluse phase thermography (*a*) and optically exicited lockin thermography (*b*) (Spiessberger *et al*., 2010).

The thermographic nondestructive method has continually been improved through applications and technological developments over the years, and becomes a reliable and commonly method used to diagnose and test the buildings structure. Few examples of the use of thermographic method with its application in the conservation field, in detecting hidden characteristics of building structures, are presented in Figs. 2,...,4.

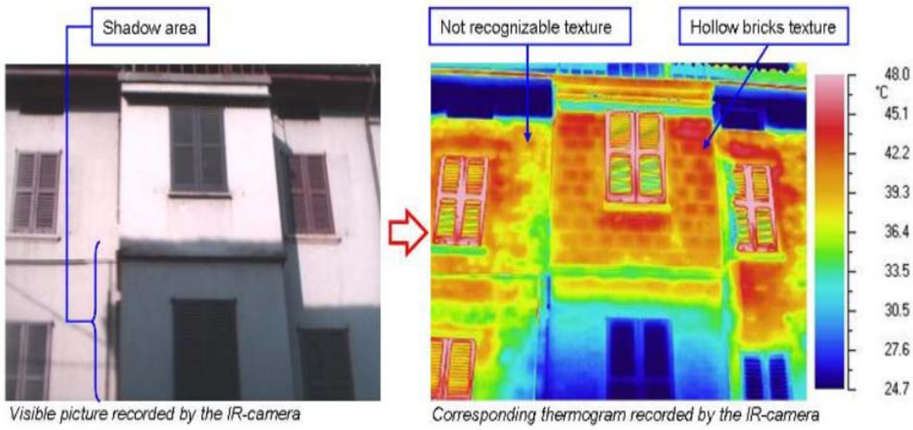


Fig. 2 – Detection of the masonry texture of an historical building; the elaborated thermogram shows an added body composed by hollow brick but the texture of the original masonry wall is not recognizable due to the thickness of the plaster and the distance of the shooting point. (Binda *et al*., 2011).

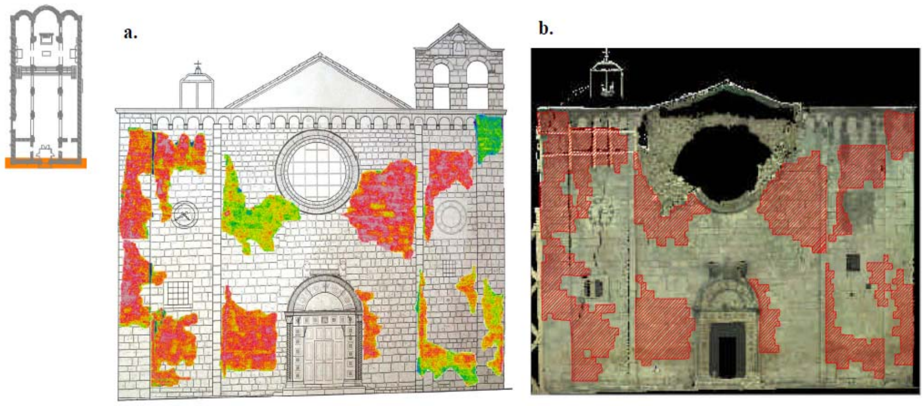


Fig. 3 – Thermographic investigation of the Sant Eusanio Forconese Church characterized by presence of gaps or technical-constructive anomalies (Bianco & Ceradini, 2010).

Passive thermography applied on the facades of the historical buildings of Athens Academy Bank of Greece in Piraeus in order to investigate, examine surface alterations. It was applied with the view to obtain thermal images with the intention of estimating their temperature distribution and detect the problematic areas. This thermal images were measured in the laboratory according to ASTM standard E1933-97 with the purpose to quantify the problematic areas (Moropoulou *et al*., 2002).

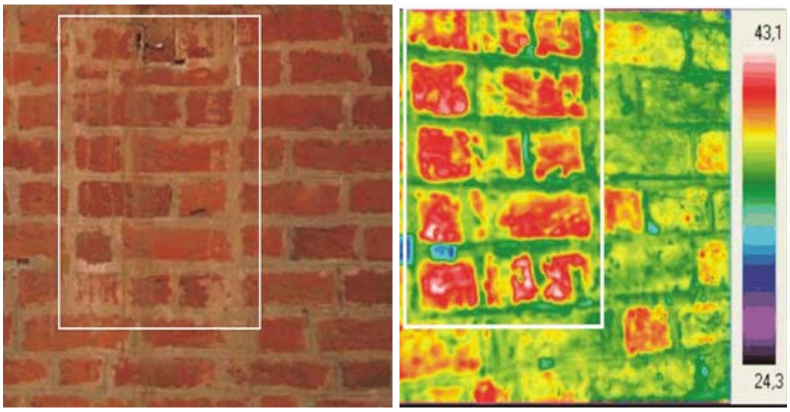


Fig. 4 – Rebricklaying in IR, church of Lady Mary in Malbork Castle (Wiecek & Poksinska, 2007).

4. IR Thermography Applications to Validate Hygrothermal Transfer in Buildings

In the thermographic camera the detector determines the traceable range of wavelengths and it's essential to stay within the area of atmospheric windows because only in these windows the atmosphere's transmissivity is high enough to detect unperturbed IR. Most cameras operate in the common two wavelength intervals of 3...5 μm or 8...12 μm. Another window exists in the near infrared between 0.78...3.0 μm.

IR radiation is an electromagnetic wave having wavelength ranges from 0.78 μm (near IR or short wavelength) to 1,000 μm (far infrared region or long wavelength). The use of "long wave" scanners filtered for the 8...12μm waveband region is most efficient for use in building inspections where the target temperatures range from 27°C to 65°C (Lo, Choi, 2004).

Specialists consider that most materials used in the building finishes processes have emission coefficients between 0.90 and 0.96 and that therefore good assessment of thermal properties of a building can be made with only one exposure with the same emissivity but *in situ* evaluation procedures revealed that there are many factors that this statement may not be always valid.

Table 1
Emission Coefficients of the Most Common Construction Materials[†]

Material	ε
Concrete	0.94
Sand	0.76
Brick	0.75...0.80
Limestone	0.95
Plaster	0.90...0.96
Glass	0.90...0.96
Wood	0.80...0.90
Roofing felt	0.93
Gypsum	0.80...0.90
Paints (all colours)	0.90...0.96
Clay	0.95
Brickearth	0.93

Different tests using four distinct values of emissivity (0.62, 0.85, 0.91 and 0.95) showed that emissivity variation induced changes in the thermal images, both during the absorption and drying periods. Thermal images obtained with an emissivity of 0.62 were different from the other images but differences among the other thermograms (emissivities 0.85, 0.91 and 0.95) were not very significant. It has been concluded that thermal images obtained with emissivity 0.85 generally had clearer isothermals. However, a wise selection of the emissivity value may simplify the thermal image's interpretation but, generally, the influence of emissivity became less important (Barreira, 2005).

Another basic condition for using thermography on buildings inspection is to be assured a difference of 20°K between the inside and the outside temperatures but even a temperature offset of 10°K is sometimes considered enough. These parameters require that examinations of buildings to be done only during the cold periods when the surrounding temperature lies around the zero point. Inside exposures have greater significance because atmospheric conditions such as wind, rain, snow or sun as well as conditions of the building itself like ventilated facades have an effect on the results of the exposure. While heat bridges can be seen from outside, there are cold bridges observable inside. Cold areas clearly stand out on walls, loft conversions, corners on the floor or window frames (Wild, 2007).

[†]Total emissivity ε for common building materials adapted from http://www.omega.com/temperature/z/pdf/z088-089.pdf

The main factors affecting the IR thermography study relevance (Stockton, 1999; Vavilov, 2010) during a building envelope thermal behaviour inspection are shown below:

a) *Climatic conditions*: insulation, wind, ambient temperature, relative humidity, greenhouse gases concentration (water vapours, CO_2).

b) *Pattern characteristics*: emissivity/reflectivity, roughness or unevenness, stains and colour of wall surface; construction of wall finish (*e.g.* extremely thick finish).

c) *Environmental deficiencies*: angle of vision and survey distance, orientation of building to the path of sunshine during the survey, existence of any heat generating plants or machines inside the building; screening objects (*e.g.* trees, shade of eaves or adjacent building).

Generally, it is possible to find leaking heating systems, faulty applied insulation or hidden timbered framework, which has been plastered over.

Nondestructive infrared thermography method reveals accurately hygrothermal transfer through building envelope systems and the most common applications of this method will be detailed in the following sections. (Snell, 2002, Balaras, 2002).

4.1. Determination of Heat Losses Through Buildings Envelope Using IR Thermography

Infrared thermography, as a method of estimating the thermal losses in building structures, is becoming increasingly popular. The classification of buildings according to their energy efficiency using IR measurements is performed by extrapolating the results of a current inspection onto the entire heating period. The thermal losses for known and respectively measured air temperatures inside and outside inspected objects can be predicted after a mathematical algorithm. In fact, the key role of IR thermography in the considered measuring procedure consists in determining the temperature distribution over the entire surface of an enclosing structure with the assumption that the heat transfer through a wall is stationary (Vavilov, 2010).

4.2. Insulation Inspection

IR thermography can easily detect missing, damaged or non-performing insulation if it is assured the minimum condition of at least 10°C stable temperature difference between the heated or conditioned space and the outside air. The inspection is typically done from both inside and outside but the best results seems to be gained from inside because of fewer influences, but a better overall understanding of the building can be revealed from larger views of the outside elevations.

Each type of insulation has a characteristic thermal pattern and is susceptible to shrinkage and cracking when poorly installed. Careful investigation done with this method can prevent an eventually huge cost of poor performance of insulation in addition to excessive energy consumption, costly freeze-ups of corner mounted water pipes or fire sprinkler systems, health issues associated with growth mold in cold spots, damage to roofs and interiors caused by ice dams, condensation and water intrusion.

In terms of the good practice the data must be collected during daytime or early evening periods because the effects of solar heat load can easily last 6...8 h on both the inside and outside after wall exposure. This often results in the direction of heat flow being reversed with poor results as confusing images and misdiagnosis. Windy conditions can quickly eliminate the thermal difference on a surface as well as enhance others thereby, in case of wind-related building problems, it is wise to conduct the inspection in a wind load conditions.

The method can be successfully applied to locate moisture in Exterior Insulation and Finish Systems (EIFS) or External Thermal Insulation Composite Systems (ETICS). Inspections are best conducted from the outside in the early evening after a sunny day with little or no wind. It may also be possible to locate moisture from inside during cooling or heating conditions as the expanded foam insulation boards tend to absorb more water over time. (Barreira, 2007).

4.3. Air Leakage Sources Identification

Air leakage problems could lead to significant energy consumed to maintain comfort parameters in buildings. The common deficiencies consist in failed window weather seal or the more complex air pathway anomalies through a plumbing chase in an interior wall or ceiling plenum.

Visualizing leakage pathway could be extremely difficult without thermal imaging. Air leakage inspections are best conducted when air flow is directed and controlled by creating a negative pressure inside using exhaust fans, specialized blower door systems, or, in larger buildings, by handling HVAC system settings. Imaging confirms that during the heating season the resulting sites of air infiltration tend to appear cooler. This kind of identification can be done during all seasons if the indoor/outdoor temperature difference is higher than a few degrees.

A complementary and more accurate method uses blower door fans to quantify air leakage rates considering that this technique is the most relevant in predicting building performance and monitoring air sealing work.

4.4. Condensation, Moisture Intrusion and Sick-Building Syndrome Diagnosis

Sick Building Syndrome groups an entire class of health-related problems that occur due to inadequate HVAC performance, moisture trapped in walls, mold growth on damp/cold thermal bridges and surfaces because of inadequate air change rates or faulty applied insulation. Many of these can be visualized and diagnosed with thermography procedures which helps diagnose very complex problems – damages in building due to condensation and mold growth, brick sprawling, roof membrane fastener corrosion and reduced insulation values.

Typically, energy efficient building design techniques must deal with both air sealing and moisture retarders to keep moisture from accumulating inside the wall sections. Locating moisture with thermography is often simple because water has both a high thermal conductivity and a high heat capacitance. However, determining the source of the moisture can be difficult because condensation, rather than leakage, is often the causer, so it is important to identify sources of air leakage that can transport moist air into the wall sections and the cold spots that can result in condensing problems.

Detection of moisture trapped in a roof system can be performed by the fact that moisture appears warmer at night after a sunny day due to its greater thermal capacitance. Notable results can be obtained if the roof surface is dry and in case of roofs with absorbent insulation.

4.5. HVAC Systems Performance Evaluation

Building auditors commonly use this method to visualize the invisible impact of the poor performance systems as indicated by excessively hot or cold areas resulted from design and installation problems transformed in excessive energy use and/or uncomfortable buildings.

For rehabilitation works, to prevent any damage, heated floors and heaters on walls can be easily identified as their position and length can be exactly determined. Heating coils are being used to provide heat to areas and rooms *via* hot water or electric cables. Thermography provides a quick way to verify location and performance of these subsurface devices. Typically, the thermal pattern shows up very clearly even when the heat source is embedded in several inches of concrete. Water leaks from pipes, whether in a wall section or under a slab, may also can be located using IR if a temperature difference is induced generally by simply running hot water through the pipe. However there are cases in which leaks under concrete slabs may not express themselves if the water is drained away in the sand/gravel base layer.

5. Conclusions

Thermographic testing non-destructive technique has the main purpose to provide information by analysing the real characteristics of the existing buildings in order to determine surface anomalies (cracks, voids, etc). Thermal irregularities, voids, air leakage, moisture intrusion and the buildings structure produce different models of superficial temperature that have characteristic shapes in a thermal image.

The high variations of temperature on the thermal images it often indicates structural changes, structural abnormalities, the lack of insulation, degradation (cracks), air leakage sources, heat losses, moisture. The infrared measurement give a qualitative image of the thermal protection level of buildings envelope and identifies the week zones hidden from eye visual contact.

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APLICAŢIILE TERMOGFRAFIERII CU INFRAROŞU LA INVESTIGAREA CLĂDIRILOR

(Rezumat)

Termografierea în infraroşu este o tehnică de investigare modernă folosită în vederea examinării clădirilor. Camerele cu infraroşu oferă un mijloc de măsurare a diferenţelor de temperatură la nivelul suprafeţei interioare cât şi a celei exterioare a elementelor investigate, astfel încât punţile termice pot fi localizate. S-a demonstrat aplicabilitatea termografie în vederea realizării evaluării gradului de izolare termică, detectării zonelor unde se produc pierderi de aer şi de căldură, stabilirii poziţiei exacte a reţelelor de furnizare a căldurii şi determinării motivelor apariţiei mucegaiului prin indentificarea zonelor cu un nivel de umiditate crescută, de asemenea, utilizarea metodei în domeniul conservării şi restaurării clădirilor monument istoric ca şi tehnică de determinare a morfologie elementelor ascunse, a degradările apărute la nivelul construcţiilor. Lucrarea îşi propune o scurtă prezentare a bazei teoretice a modului de utilizare a metodei termografice în inflaroşu ca tehnică de investigare a construcţiilor.